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The Moisture Observation Pre-processing System (MOPS)

by

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Abstract

The Moisture Observation Pre-processing System (MOPS) has been developed to provide cloud data for the New Mesoscale Model (NMM). It has been adapted from the Interactive Mesoscale Initialisation (IMI), which was used to generate the initial conditions for the Old Mesoscale Model (OMM). It uses satellite and radar imagery, surface observations, human interactive monitoring and modification, and model-based and empirical rules to generate a three dimensional cloud analysis. It has been necessary to develop Forward and Backward Interpolation steps, as the MOPS works on the OMM grid and levels. The cloud values are converted into relative humidity profiles and assigned observation errors before being assimilated into the NMM by the Analysis Correction (AC) Scheme in the same way as radiosonde humidity data, but with a single grid-point of influence.

1 Introduction

The New Mesoscale Model (NMM) is a version of the Unified Model (UM) (Cullen [6]), and as such uses the Analysis Correction (AC) data assimilation scheme (Bell et al [5]) to 'nudge' the model state toward the observations over two 3-hour assimilation periods (Macpherson et al [14]). This approach allows the model state to remain close to balance throughout the assimilation period, avoiding the 'shock' caused by an instantaneous analysis, as used in the Old Mesoscale Model (OMM) (Golding [7]); the OMM experienced loss of cloud and excessive convection in the early stages of the forecast, as a result of the imbalances caused by this initialisation shock.

However, the AC scheme, as used by both the Global Model and the Limited-Area Model (LAM), assimilates a very limited amount of moisture data: only radiosonde humidities. As cloud is one of the main mesoscale forecast variables, it is considered important to include more moisture data in the analysis. This has been achieved through the development of the Moisture Observation Pre-processing System (MOPS) (Macpherson and Wright [13]).

The MOPS, an interactive system requiring the supervision of a human analyst (a forecaster), uses a model first-guess, satellite and radar imagery and surface observations to generate a three-dimensional cloud analysis. This is realised through a sequence of two-dimensional analyses of cloud and precipitation variables, which are monitored by the human analyst, and the application of model-based and empirical rules to extend the use of the data and the analyses to three dimensions (see figure 1 for the sequence of analyses). The MOPS is based on the Interactive Mesoscale Initialisation (IMI) (Wright et al [20, 21, 22]) which was developed and used to generate the initial conditions for the OMM. Although, the IMI provided a full set of initial model fields from which to run the OMM, the emphasis in the development of the IMI was always on the analysis of moisture data. For this reason, it was a fairly simple task to adapt the IMI to provide solely cloud data, and this approach was adopted as the starting point for the MOPS. However, the OMM and NMM use different grid and level structures, which has made it necessary to also develop Forward and Backward Interpolation steps to map the data between the two.

The MOPS 'product' is a three-dimensional cloud analysis. However, it is convenient to convert the cloud data to profiles of relative humidity, before assimilating them in much the same way as radiosonde ascents.

Figure 2 shows how the MOPS fits in to the mesoscale data assimilation scheme and figure 3 shows a flow chart for the MOPS. The MOPS analysis is described in detail in section 2. The Forward and Backward Interpolations are described in section 3. The assimilation of the MOPS data, including the diagnosis of relative humidity, is described in section 4. Section 5 discusses some of the plans and ideas for the future development of the system.

A different way of incorporating cloud information in the model is the direct assimilation of satellite data by the AC scheme. This approach is being developed independently for the Global Model and the LAM by Richards [16].

2 The MOPS analysis

The MOPS analysis is a menu-driven system, controlled by 'mouse' input (and keyboard where required), which is operated by a human analyst (a forecaster) on an interactive graphics workstation. At present, the workstation is an IBM5080 graphics terminal; this is a 'dumb' terminal with all the processing carried out on the mainframe, an HDS EX100. The system allows the analyst to monitor the use of satellite and radar imagery, and surface observations in the production of a set of moisture analyses: precipitation rate and phase, total cloud cover, cloud top height and cloud base height. These analyses are then used, with additional information from the surface cloud reports, to modify the first-guess cloud fields to generate a three-dimensional cloud analysis, through the use of empirical and model-based rules. A further option to modify profiles of cloud allows the analyst a chance to check and modify the vertical cloud structure after the analysis. Before the sequence of analyses, the forecaster has a chance to check the imagery, some of which is used automatically in the subsequent analyses: a Meteosat infrared image, a Meteosat visible image (if available), a FRONTIERS radar rainfall image and Sferics lightning location reports.

The MOPS analysis is imbedded in the Mesoscale Graphics Facility (MGF) (Wright and Golding [23], Golding et al [8]), a versatile graphics display package developed to look at the data sources connected with the OMM. The MGF was developed as an interactive system, but can be used in 'batch'. The primary reason for maintaining the interactive component of the MOPS analysis, which was such a central part of the IMI, is the danger of introducing gross errors in the total cloud cover and cloud

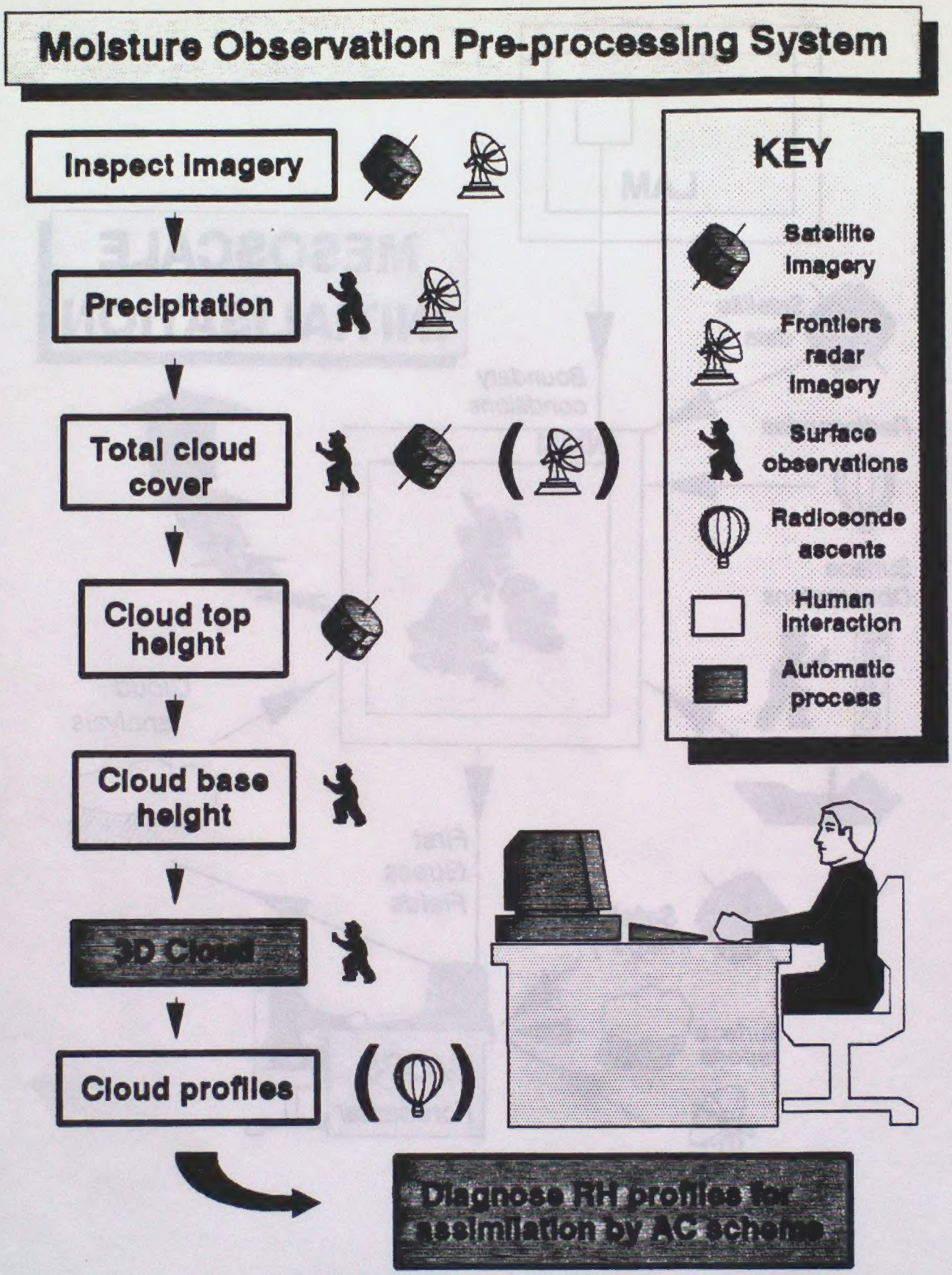

Figure 1: MOPS sequence of analyses and data sources

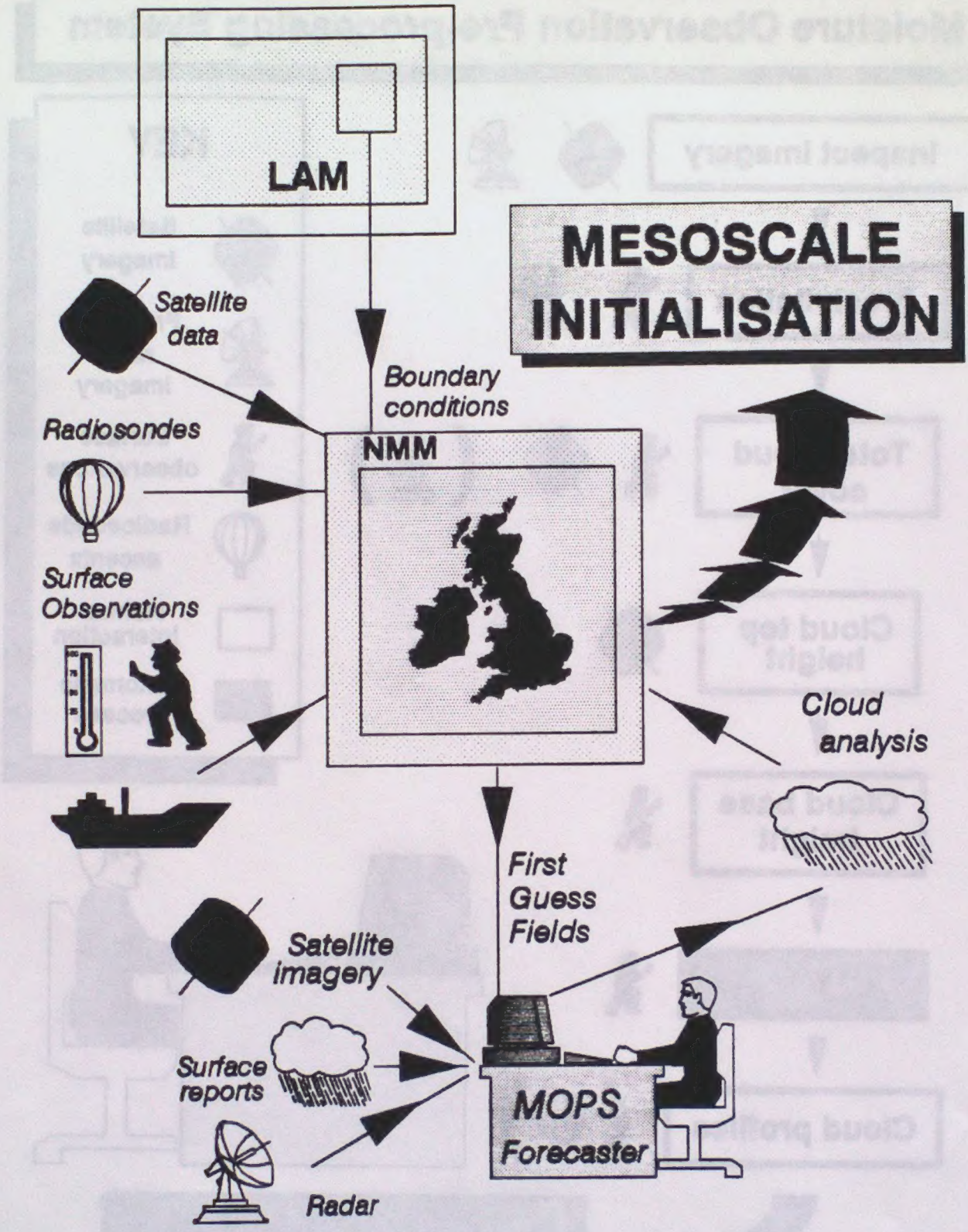

Figure 2: The New Mesoscale Model data assimilation scheme

MOPS Flow Chart

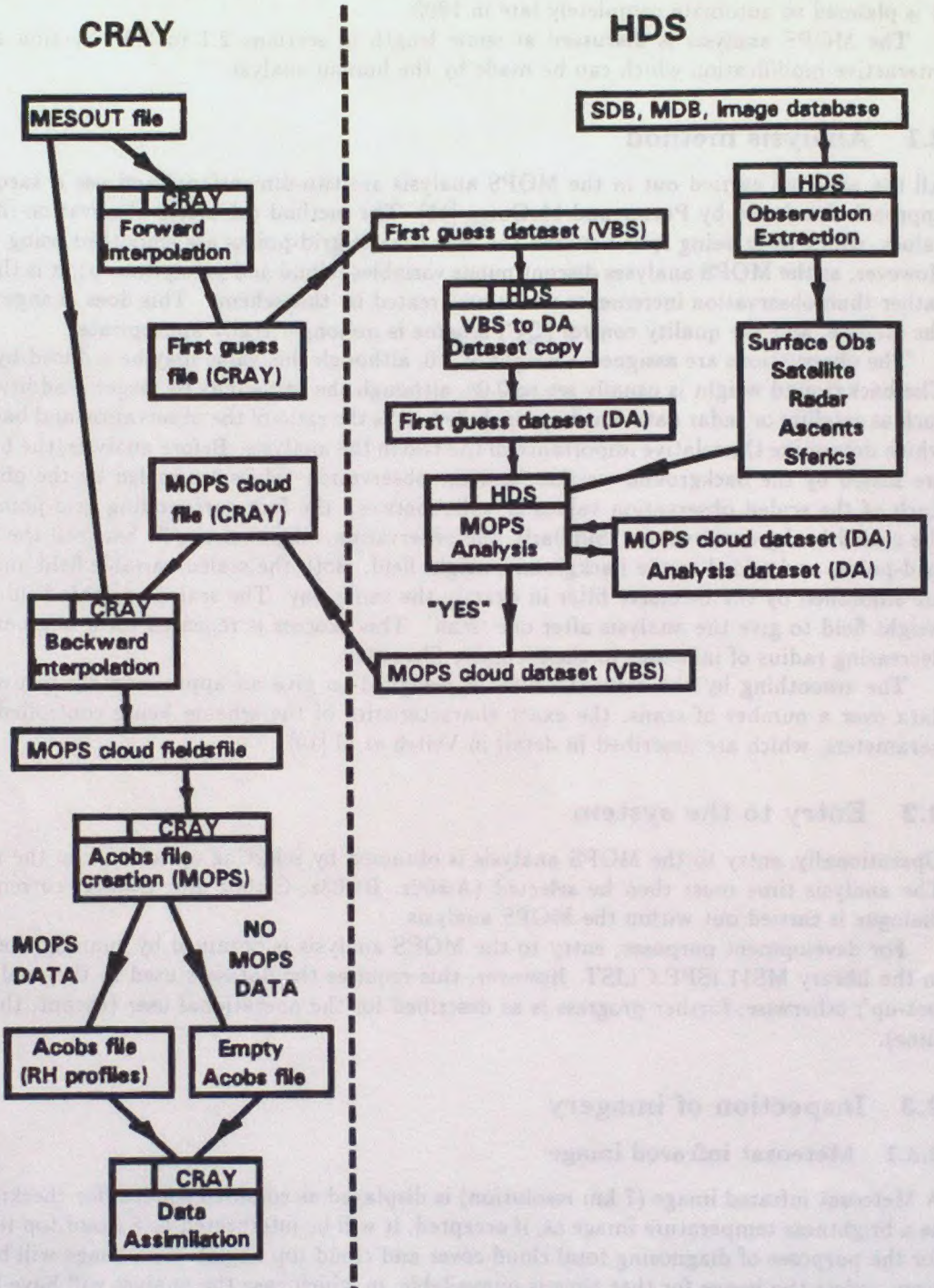

Figure 3: Flow chart for the Moisture Observation Pre-processing System (MOPS)

top height fields when using satellite data automatically (these problems are mentioned in sections 2.4.2 and 2.4.4). However, work is underway to develop safer methods of diagnosing these two quantities, and it is planned to automate completely late in 1993.

The MOPS analysis is discussed at some length in sections 2.1 to 2.5. Section 2.6 discusses the interactive modification which can be made by the human analyst.

2.1 Analysis method

All the analyses carried out in the MOPS analysis are two-dimensional and use a successive correction approach developed by Purser and McQuigg [15]. The method calculates observation-minus-background values, which after being split between the four nearest grid-points are smoothed using a recursive filter. However, as the MOPS analyses discontinuous variables (cloud and precipitation), it is the absolute values rather than observation increments which are treated by this scheme. This does change the properties of the scheme, and the quality control (QC) scheme is no longer really appropriate.

The observations are assigned a weight of 1.0, although this value may be reduced by the QC scheme. The background weight is usually set to 0.04, although the value may be larger if additional information, such as satellite or radar data, has been included. It is the ratio of the observation and background weights which determine the relative importance of the two in the analysis. Before analysis, the background values are scaled by the background weights, and the observation values are scaled by the observation weight. Each of the scaled observation values is 'split' between the four surrounding grid-points, and added to the scaled background values. Similarly, the observation weights are split between the four surrounding grid-points and added to the background weight field. Both the scaled variable field and the weight field are smoothed by the recursive filter in exactly the same way. The scaled variable field is divided by the weight field to give the analysis after one 'scan'. This process is repeated for a number of scans, with a decreasing radius of influence in the recursive filter step.

The smoothing by the recursive filter is designed to give an approximately Gaussian spreading of data over a number of scans, the exact characteristics of the scheme being controlled by a number of parameters, which are described in detail in Veitch et al [19].

2.2 Entry to the system

Operationally, entry to the MOPS analysis is obtained by selecting option 'O' on the main CFO panel. The analysis time must then be selected (A=00z, B=03z, C=06z and D=21z, currently). All further dialogue is carried out within the MOPS analysis.

For development purposes, entry to the MOPS analysis is obtained by running the Clist BWMOPS in the library MS11.ISPF.CLIST. However, this requires the datasets used in the analysis to have been 'set-up'; otherwise, further progress is as described for the operational user (except, there is no 'cut-off' time).

2.3 Inspection of imagery

2.3.1 Meteosat infrared image

A Meteosat infrared image (7 km resolution) is displayed as coloured squares for checking; it is displayed as a brightness temperature image as, if accepted, it will be interpreted as a cloud top temperature image for the purposes of diagnosing total cloud cover and cloud top height. The image will be for the analysis time, unless the image for that time is unavailable, in which case the analyst will have been requested to select another image (the most recent) at an earlier stage. In general the image will be accepted after a cursory inspection, but if the image is somehow corrupt, then the analyst will select another image. If the final image selected is an 'off-time' image, for whatever reason, the analyst will be asked whether the image should be used automatically or not.

2.3.2 Meteosat visible image

Unlike the infrared image the Meteosat visible image (7 km resolution) is displayed simply for information, and the analyst will proceed to the next stage after inspecting it.

2.3.3 Radar rainfall image

A FRONTIERS (quality-controlled) radar rainfall image (5 km resolution) is displayed as coloured squares for the analyst to check; if the image is approved it will be used automatically in the precipitation analysis. The image will be for the analysis time, unless the image for that time is unavailable, in which case the analyst will have been requested to select another image (the most recent) at an earlier stage. In general the image will be accepted after a cursory inspection, but if the image is somehow corrupt, then the analyst will select another image. If the final image selected is an 'off-time' image, for whatever reason, the analyst will be asked whether the image should be used automatically or not.

2.3.4 Sferics reports

If a Sferics (lightning location) dataset has been allocated, then any reports for the analysis time will be displayed for reference; these data are not used in the analysis. The analyst will proceed to the next stage after inspecting the reports.

2.4 The analyses

2.4.1 Precipitation rate and type analysis

The model first-guess dynamic and convective precipitation rates are summed to obtain the first guess total precipitation rate, and the phase of the precipitation (indicated by the sign) is taken from the dynamic precipitation rate. If a FRONTIERS radar rainfall image is available for the correct time, a mean precipitation rate is extracted for all grid-points within the radar domain, and used to replace the first-guess. Where the radar is used, the phase of the first-guess is preserved. Absolute values of less than 0.03 $mm\,hr^{-1}$ are set to zero. A fractional precipitation cover is also extracted within the radar domain for each grid-point by assuming all pixels with values greater than 0.1 $mm\,hr^{-1}$ to be full cover.

Present weather reports and hourly rainfall accumulations are interpreted as instantaneous precipitation rates, before being used in the analysis. If neither a present weather report nor an hourly accumulation is available for a particular observation site, then no precipitation rate is extracted for that particular site. Otherwise, the extraction proceeds as follows for each observation.

The first-guess precipitation rate is extracted from the grid-point nearest to the observation point. If the present weather code is 76 (diamond dust), 78 (isolated snow crystals), 98 (thunderstorm combined with dust storm or sandstorm) or is in the range 1 to 13, 17 to 49 (no precipitation or precipitation in the preceding hour, but not at observation time) then the precipitation rate is set to zero and the phase is nominally set to that of the first guess. If the present weather code is in the range 14 to 16 (precipitation within sight, but not at the station) then precipitation rate is set to that of the first-guess, with the phase assumed to be liquid. For all other present weather codes (precipitation at the station), the precipitation rate is set to the first-guess rate, but constrained to be within a range appropriate to the particular present weather code (values given in table 1).

If an hourly accumulation is available, then the precipitation rate is set to that of the first-guess, but constrained to be within $\pm 0.19\ mm\,hr^{-1}$ of the hourly accumulation; this reflects the uncertainty of translating an hourly rainfall accumulation into an instantaneous rainfall rate. The phase of the precipitation is taken from the first-guess.

For the analysis, an increased background weight of 0.25 is used where the radar has been incorporated, as compared with a value of 0.04 elsewhere. The smoothing radius in the recursive filter is set to 4 grid-lengths, decreasing to 1 where the data are dense. In this process, the first guess is effectively smoothed to 4 grid-lengths. Two separate analyses are performed: one of the precipitation rate and one of the precipitation phase (positive values indicating liquid precipitation, negative values indicating frozen precipitation). Precipitation rates below 0.02 $mm\,hr^{-1}$ are set to zero.

The analysis is displayed as coloured squares, with the diagnosed instantaneous rates superimposed. The standard MOPS options for modification (see section 2.6) are available, with the addition of copying in the radar rainfall, which may replace the analysis values either over the entire area of coverage or only in those areas where the radar rainfall rate is greater than 0.1 $mm\,hr^{-1}$. The former is generally more appropriate for convective precipitation where the radar sees well to the full extent of its nominal range and the analysis is likely to give a poor representation due to the low resolution of the surface reports. The latter is more appropriate to frontal precipitation, where in general the radar does not see to the

Table 1: Precipitation rates ($mm\,hr^{-1}$) associated with Present Weather codes (negative values indicate the ice phase)

Description	*Code numbers*	*Min. rate*	*Max. rate*
Intermittent slight drizzle	50	0.01	0.10
Continuous slight drizzle	51	0.02	0.10
Intermittent moderate drizzle	52	0.10	0.50
Continuous moderate drizzle	53	0.10	0.50
Intermittent heavy drizzle	54	0.50	2.00
Continuous heavy drizzle	55	0.50	2.00
Slight freezing drizzle	56	0.01	0.10
Moderate/heavy freezing drizzle	57	0.10	0.50
Slight drizzle and rain	58	0.02	0.50
Moderate/heavy drizzle and rain	59	0.50	4.00
Intermittent slight rain	60	0.02	0.50
Continuous slight rain	61	0.05	0.50
Intermittent moderate rain	62	0.50	4.00
Continuous moderate rain	63	0.50	4.00
Intermittent heavy rain	64	4.00	9.90
Intermittent heavy rain	65	4.00	9.90
Slight freezing rain	66	0.02	0.50
Heavy freezing rain	67	0.50	4.00
Slight rain or drizzle and snow	68	-0.01	-0.50
Moderate/heavy rain and snow	69	-0.50	-4.00
Intermittent slight snow	70	-0.01	-0.50
Continuous slight snow	71	-0.02	-0.50
Intermittent moderate snow	72	-0.50	-4.00
Continuous moderate snow	73	-0.50	-4.00
Intermittent heavy snow	74	-4.00	-9.90
Continuous heavy snow	75	-4.00	-9.90
Diamond dust	76	specified elsewhere	
Snow grains	77	-0.01	-0.10
Isolated snow crystals	78	specified elsewhere	
Ice pellets	79	-0.10	-0.50
Slight rain showers	80	0.01	1.00
Moderate/heavy rain showers	81	0.20	9.90
Violent rain showers	82	5.00	9.90
Slight rain and snow showers	83	-0.01	-0.50
Moderate/heavy rain/snow showers	84	-0.50	-9.90
Slight snow showers	85	-0.01	-0.50
Moderate/heavy snow showers	86	-0.50	-9.90
Slight small hail showers	87	-0.10	-0.50
Moderate/heavy small hail showers	88	-0.50	-9.90
Slight hail showers	89	-0.10	-0.50
Moderate/heavy hail showers	90	-0.50	-9.90
Slight rain (Cb in previous hour)	91	0.10	0.50
Moderate/heavy rain (Cb previous hr)	92	0.50	9.90
Slight snow (Cb in previous hour)	93	-0.10	-0.50
Moderate/heavy snow (Cb previous hr)	94	-0.50	-9.90
Slight/moderate thunderstorm	95	0.10	5.00
Slight/moderate thunderstorm(hail)	96	-0.10	-0.50
Heavy thunderstorm	97	1.00	9.90
Heavy thunderstorm with dust storm	98	specified elsewhere	
Heavy thunderstorm (hail)	99	-1.00	-9.90

Table 2: Precipitation cover values (oktas) diagnosed from the precipitation rate after the analysis

Precipitation rate ($mm\,hr^{-1}$)	Precipitation cover (oktas)
0.0	0.0
0.1 — 0.5 (where radar not used)	$\frac{precipitation\ rate}{16}$
> 0.5	8.0

full extent of its nominal range, and the smoothness of the analysis is likely to accord with reality. The phase of the original precipitation (first-guess or analysis) is preserved when the radar data are inserted.

The fractional precipitation cover is updated after the final precipitation analysis has been accepted; the precipitation cover values set depend on the intensity of the analysed precipitation (see table 2).

2.4.2 Total cloud cover

The first-guess total cloud cover field is replaced by a cloud cover field derived from a temperature-calibrated Meteosat infrared image over its area of coverage, if such an image is available. Satellite pixels with a temperature 10 deg C or more lower than the first-guess surface temperature are assumed as cloud filled. The cloud cover for each grid-square is set equal to the fraction of the pixels within that grid-square which are diagnosed 'cloudy'. This threshold of 10 deg C colder than surface temperature can cause problems over a cold land surface in winter, where the cloud top temperature of a stratocumulus sheet may be similar to that of the ground. Finally, the first-guess cloud cover is set equal to the maximum of itself and the precipitation cover calculated from the radar image and precipitation analysis (see section 2.4.1).

Observed total cloud cover reports of 7 oktas cover are set to 7.3 oktas and those of 1 okta to 0.7 oktas; this takes account of the interpretation that any gap in an otherwise overcast sky is 7 oktas cover and any small wisp of cloud in an otherwise clear sky is 1 okta cover.

If a temperature-calibrated infrared satellite image has been used, the maximum smoothing radius in the analysis is reduced from 4 to 2 to reflect the higher accuracy of the cloud cover first-guess. Following the analysis, cloud cover values of less than 1 okta are set cloud-free to give the cloud a clearly defined edge.

The analysis is displayed as coloured squares, with the surface observations of total cloud cover superimposed. The standard MOPS options for modification (see section 2.6) are available,with the addition of an option to recalculate the cloud cover from the Meteosat infrared image.

2.4.3 Adjustment of satellite temperatures for partial cloud cover

If a temperature-calibrated infrared Meteosat image is available, then it is adjusted for ground radiation effects using the total cloud cover analysis. Each satellite pixel is adjusted, using the total cloud cover value from the grid-square corresponding to the pixel. If the cloud cover at this grid-point is greater or equal to 7 oktas, no adjustment is made to the pixel value. If the cloud cover is less than or equal to 2 oktas, the pixel value is set to a missing data value, to ensure that pixel is not used in the calculation of cloud top height. If the cloud cover is in the range 2 to 7 oktas, then a new satellite temperature is set as follows:

$$T_{new} = \sqrt[4]{\frac{24T^4 + (8-N)T_{surf}^4}{16-N}} \qquad (1)$$

where T is the original satellite brightness temperature, T_{new} is the temperature which has been adjusted to account for the effect of partial cloud, T_{surf} is the first guess surface temperature and N is the analysed total cloud cover in oktas; all temperatures are in Kelvin.

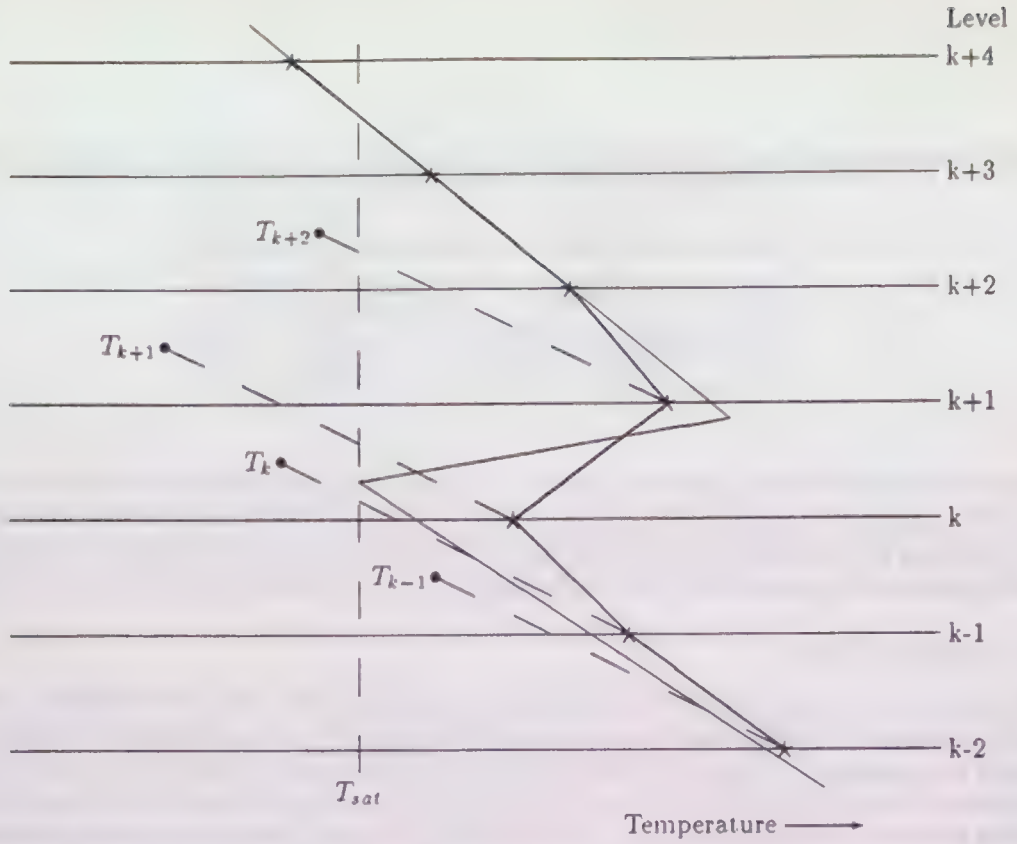

Figure 4: An illustration of the problems of correctly assigning a cloud top height using a satellite brightness temperature and a model temperature profile (thick solid line and stars indicate the model temperature, thin solid line indicates the real temperature and thin dashed lines indicate the dry adiabatic lapse rates followed in diagnosing a temperature for cloud detection, T_k).

2.4.4 Cloud top height and improved guess cloud distribution

The cloud top height field is derived from the first guess cloud distribution. If a Meteosat infrared image is available, then the 'cloud top temperature image' (the adjusted satellite image) is used to define a cloud top height field which replaces the model cloud top height within the satellite image domain; the cloud top is taken as the highest model level for which at least $\frac{1}{8}$ of the satellite pixels in the model grid-square are colder than the first-guess-derived temperature at that level.

The first-guess temperature is diagnosed as follows. At each level in turn, the first-guess temperature at the top of the cloud layer for that level (the half-level above) is calculated from pressure and potential temperature values, as shown in equations 2 and 3.

$$\pi_{k+\frac{1}{2}} = \left(\frac{p_k + p_{k+1}}{2p_{ref}} \right)^{\frac{R}{C_p}} \tag{2}$$

$$T = \pi_{k+\frac{1}{2}} \theta_{k-1} \tag{3}$$

where T is the diagnosed temperature for the half-level above the current level, $\pi_{k+\frac{1}{2}}$ is the exner pressure at the same half-level, p_k is the pressure at level k, p_{ref} is the reference pressure (1000 mb), θ_{k-1} is the potential temperature at the level below the current level, R is the gas constant and C_p is the specific heat capacity at constant pressure. The potential temperature value is taken from the level below, simulating a dry adiabatic lapse rate from the level below to the half-level above, which will be more extreme than any expected profile, thus should improve the chance of detecting inversions which are not fully resolved in the first-guess temperature profile. This is illustrated in figure 4, where the real temperature profile (thin solid line) shows a sharp inversion, which is not well-resolved by the model profile (thick solid line). Diagnosing the temperature by following a dry adiabat (thin dashed line), produces a temperature estimate T_k for level k which will successfully detect the top of the cloud layer at that level.

The first-guess cloud distribution is also refined using the satellite image and the diagnosed temperature. At the bottom level an initial 'satellite cloud cover' value is set equal to the fraction of pixels within the grid-square in the cloud top temperature image which are colder than the derived first-guess temperature. However, this value is limited to be less than or equal to the analysed total cloud cover. At all subsequent levels a similar satellite cloud cover value is extracted (the fraction of pixels colder than the temperature for that level). This satellite cloud cover represents the cloud above the current level, and therefore is considered as being the cloud cover value at the level above the current level (i.e. the satellite cloud value for level $k+1$, N^{sat}_{k+1}, is diagnosed using the level k temperature).

Modifications are applied to the first-guess cloud using the satellite cloud cover. If the satellite cloud cover for that level, N^{sat}_k, is non-zero, then an improved-guess cloud cover value is set using equation 4.

$$N^{new}_k = Max\left(N^{sat}_k - N^{sat}_{k+1}, Min(N^{sat}_k, N_k)\right) \tag{4}$$

where N^{new}_k is the improved-guess cloud cover at level k, and N^{sat}_k is the satellite cloud cover at level k, which is the fraction of pixels colder than the diagnosed temperature for that level. All these cloud cover values are in oktas.

If the satellite cloud cover for the level is zero, then the new cloud cover is set to zero. The changes to the cloud cover produced by this diagnosis of an improved-guess will be fairly small, in general. Cloud is only increased where the change in satellite cloud cover between the current level and the level above exceeds the first-guess cover at the current level, which is then set equal to the difference in the satellite covers. Cloud is only reduced where the satellite cloud cover for the level is less than the first-guess cover, which is then set equal to the satellite cover. This means that changes are only made on the basis of what is 'seen' by the satellite; no assumptions are made about the cloud at other levels which are hidden.

The improved-guess cloud top height field is displayed as coloured squares. The standard MOPS options for modification (see section 2.6) are available, with the addition of an option to re-derive the cloud top height (and improved-guess cloud distribution) from the satellite image. When any adjustments are made to the cloud top heights, the cloud distribution is modified to reflect these changes: cloud above the the new cloud top is removed and a specified cloud cover value is inserted at the new top. All these adjustments are subject to the limit of the analysed total cloud cover.

2.4.5 Extraction of improved-guess cloud profiles at observation points

Profiles of cloud amount at model levels are extracted at all observation points by a bi-linear interpolation from the nearest 4 grid-points.

2.4.6 Cloud base height

The first-guess cloud base is set equal to the height of the first level with at least 1 okta cloud cover. The cloud base observations are taken from the low cloud base report and the first 8-group report; if the 8-group base is present it is used in preference to the low cloud base.

After analysis, where the total cloud cover analysis has a value less than 1 okta, the cloud base height is set to 49999 feet and the cloud top height is set to -1 feet, indicating the absence of significant cloud at that grid-square. Where the cloud base height analysis is below 8000 feet, the cloud top height is forced to be at least 500 feet above the base. Elsewhere the cloud base is forced to be at least 500 feet lower than the cloud top or 8000 feet, whichever is higher.

The cloud base analysis is displayed as coloured squares with the surface observations of cloud base in hundreds of feet superimposed. Options for modification are standard. When any adjustments are made to the cloud base heights, the cloud distribution is modified to reflect these changes, as with the cloud top heights (section 2.4.4). Consistency between the cloud top height and cloud base height is maintained as described above, and cloud cover values may never exceed the analysed total cloud cover.

2.4.7 Multi-level cloud analysis

The surface observations of cloud and present weather (see table 3) are interpreted in terms of cloud profiles with values at model levels. The cloud top height is interpolated bi-linearly to observation points and used to set the cloud depth. The interpretation is sectioned into height regimes (some of which overlap): fog, low cloud, medium cloud and high cloud (see table 4) observations are interpreted in using the improved-guess cloud cover, the cloud top height and some empirical rules, which are designed to 'get the most' out of the observations.

Table 3: Observations used within the multi-level cloud analysis

Number	Variable
1	Station height (m)
2	Weather type
3	Total cloud cover (oktas)
4	Low cloud cover (oktas)
5	Low cloud type
6	Low cloud base (feet)
7	Medium cloud type
8	High cloud type
9	Number of 8-groups
10	1st 8-group cloud cover (oktas)
11	1st 8-group cloud type
12	1st 8-group cloud base (feet)
13	2nd 8-group cloud cover (oktas)
14	2nd 8-group cloud type
15	2nd 8-group cloud base (feet)
16	3rd 8-group cloud cover (oktas)
17	3rd 8-group cloud type
18	3rd 8-group cloud base (feet)
19	4th 8-group cloud cover (oktas)
20	4th 8-group cloud type
21	4th 8-group cloud base (feet)

Table 4: Cloud boundary heights

Cloud boundary	Level
Low cloud (lower)	1st level above 20 m
Fog (upper)	1st level at or below 200 m
Low cloud (upper)	1st level at or below 2200 m
Medium cloud (lower)	Level above low cloud upper boundary
Medium cloud (upper)	1st level at or below 5600 m
High cloud (lower)	Level above medium cloud upper boundary
High cloud (upper)	Level below top

Table 5: Specification of cloud depth and cover for 8-group reports.

Code	Type	Depth	Cover
5[1]	Nimbostratus	Max(1000 m, analysed top)	Reported cover
8	Cumulus	Max(500 m, analysed top)	Min(4 oktas, reported)
9	Cumulonimbus	Max(1000 m, analysed top)	Min(4 oktas, reported)
Others	General	200 m	Reported cover

Table 6: Specification of cloud depth and cover for low cloud reports

Code	Type	Depth	Cover
0	No St/Sc/Cu/Cb	Max(1000 m, analysed top) (for medium cloud type 2: dense altostratus) 500 m (otherwise)	reported cover
2	Moderate Cu	Max(500 m, analysed top)	Min(4 oktas,reported)
3 and 9	Cb	Max(1000 m, analysed top)	Min(4 oktas,reported)
5-8	St and/or Sc	500 m	reported cover
Others	Small Cu/Sc	200 m	reported cover

If the low cloud cover is greater than 5 oktas, then the medium and high cloud types are set to missing data indicators, as it is assumed the observations of these quantities may not be of high quality. If no low cloud cover value is being reported, but the low cloud base below 8000 feet is, then the low cloud cover is set equal to the total cloud cover, and any cloud below the observed low cloud base is removed. Below 8000 feet, where low cloud exists in the improved-guess and low cloud is observed, it is restricted to the observed low cloud amount. Between 8000 and 18000 feet, where there is no medium cloud observed, cloud is removed. Above 18000 feet, where there is no high cloud observed, cloud is removed. At levels not covered by the other conditions, cloud is limited to the analysed total cloud cover. If sky obscured is reported, then 8 oktas cloud cover is set at all levels from the low cloud lower level to the fog upper level (see table 4), and no further changes are made to the cloud profile at that location.

The 8-group reports are interpreted for each observation point in turn, if they are present. Cloud is removed from the levels between the last level processed by the previous 8-group (0 for the first 8-group) and the level corresponding to the base height of the current 8-group cloud. The cover and depth of the cloud to be set in the profile are then determined by the cloud type (see table 5). This cloud cover value is set at the levels from the 8-group cloud base up to the designated cloud top level.

If no 8-groups are included in a particular observation, a greater use is made of the cloud information in the main report. The level corresponding to the observed low cloud base height is located, and the cloud cover and depth set depending on the cloud type (see table 6). If high cloud is reported, then the cloud cover at the level with the greatest cloud cover value in the improved-guess profile between the high cloud lower and upper levels (see table 4) is set to the observed total cloud cover. If no cloud is present in the improved-guess profile at these levels, the observed total cloud cover is inserted at the first level at or below 8000 m. If medium cloud is being reported, then the cloud cover at the level with the greatest cloud cover value in the improved-guess profile between medium cloud lower and upper levels (see table 4) is set to the observed total cloud cover; if high cloud is also being reported it is set to observed total cloud cover minus 1 (but limited to be at least 1 okta). If no cloud is present in the improved-guess profile at these levels, the diagnosed cloud cover value is set at the mid-level between the medium cloud lower and upper levels.

An analysis is carried out for each model level, with the improved-guess cloud acting as the background and the profiles (incorporating both improved-guess and observation information) acting as point observations. A background weight of 0.04 is used within the recursive filter. Analysis cloud above 8000 feet which is above the analysed cloud top is removed; if cloud above the top is present below 8000 feet, the top is reset to the height of the analysis cloud. Analysis cloud below the cloud base height analysis is removed. The cloud at all levels is scaled by the ratio of the analysed total cloud and the maximum cloud at any height as diagnosed by the multi-level cloud analysis. This ensures that at least one model level has the analysed cloud cover, and that no levels exceed the analysed cover. Cloud values less than 1 okta are set cloud-free, those greater than 7 oktas are assigned full cloud cover.

2.4.8 Temperature and precipitation dependent adjustments to cloud

Some semi-empirical adjustments using the precipitation analysis and the temperature profiles are applied to the 3D cloud analysis; these are based on the OMM precipitation physics, but probably still have a beneficial impact. Where no appreciable precipitation has been analysed, two cloud-free layers are inserted about the $-15\,\mathrm{deg}\,C$ level, if not already present, to ensure the lower cloud does not glaciate. Where

light precipitation has been analysed, the highest cloud-free layer in between the 0 deg C level and the -15 deg C level is assumed to be the level to which glaciation occurs, and is reinforced by removing any cloud from the level directly below. Where moderate or heavy precipitation has been analysed, 8 oktas cloud cover is set for all levels in between and including the 0 deg C level and the -15 deg C level, allowing glaciation to occur down to the 0 deg C level. The idea of glaciation depending on seeding is strictly only applicable to the OMM, and not the NMM (see Golding and Ballard [10] and Smith and Gregory [17]).

2.4.9 Interactive adjustment of cloud profiles

The analyst is able to select a series of points on a cloud top height field display and inspect and modify the cloud profiles at these points. The profiles are displayed on a tephigram background, temperature is also displayed as a line plot to aid interpretation, with cloud displayed as a series of numbers (values in oktas) plotted at the temperature positions. If radiosonde ascents are present within a prescribed radius of the selected location and for a recent time (within 6 hours of analysis time), the closest ascent is displayed in a temperature/dew point form. The times of the ascents, which fall within the time window, are plotted on the cloud height field display in hours relative to midnight.

If the cloud values for a profile are being modified, a point on the profile display is selected using the mouse. The nearest point on the profile is automatically located, and is modified by selecting a new value from a menu selection of 0,1,2,3,4,5,6,7,8. Any number of changes can be made to the cloud profiles, once the modification option has been selected. In addition, the option to modify the cloud can be selected several times before the cloud profile is accepted; this is useful when it is necessary to zoom the picture to apply modifications at low levels, having already adjusted upper levels on the unzoomed picture. When the analyst is satisfied with the cloud profile, an area within which the updated cloud values are set is selected on the cloud height field display. Only those values of the profile which have been changed are applied to the selected area.

After the profiles at all the selected locations have been examined, and adjusted if required, the analyst is asked if any more profiles are required. If so, the procedure described above is repeated. Otherwise the cloud analysis is complete.

2.5 Automatic completion and acceptance of cloud analysis

2.5.1 Automatic procedure

At various stages in the analysis procedure, it is possible for the MOPS analysis sequence to go into 'automatic' mode, in which the remaining tasks are completed without further input from the analyst. This process can be initiated in two ways: due to a shortage of time, the program can 'decide' to go into automatic mode, having other pressing tasks, the analyst may opt to set the MOPS analysis into automatic mode. Either of these events will prompt the forecaster being questioned on the use of the data (see section 2.5.2).

2.5.2 Acceptance of the MOPS analysis

On completion of the MOPS analysis sequence, or if the procedure goes into automatic mode (see section 2.5.1), then the analyst is asked to confirm that the final output should be used. If the analyst accept the final MOPS analysis, then it will be copied to a Cray transfer dataset for use in the data assimilation (the remaining tasks having, first, been completed automatically if the procedure goes into automatic mode). If not, the program will immediately complete, without copying the data to the Cray transfer dataset (and without completing any tasks which may remain); the MOPS analysis data will not be used in the data assimilation.

2.6 Modification options

The MOPS analysis allows a wide range of changes to the 2D analyses to be made interactively by the human analyst (for more detail, see sections 2.0 and 2.1 of Golding [11]). Changes are usually applied in one of two ways: to the analysis; to the first-guess and/or observations, before re-analysis.

The modifications to the first-guess or analysis are carried out in the same manner: the set of points to be modified are selected, and then the type and magnitude of the change area is input. The selection of points can be: a single point, a line, an area or an area covered by values in a range in any stored

field (selection is made on screen using the mouse). The changes can be: set a value, apply a correction, multiply by a factor, copy values from another field or image, add values from another field, analyse specified values (with a value typed in). It can be seen that these options allow a very wide range of changes to be made, but are not specific to the particular analyses, and so not all allowed options are appropriate.

The modifications to observations which are usually made before re-analysis include deleting observations, correcting observations and creating new (bogus) observations.

There are also general display options which allow the forecaster to hide, move, delete or zoom pictures or fields within pictures. For move detail on the display aspects of the system see Wright and Golding [23].

3 Interpolations

The first-guess data for the MOPS comes from a 'Mesout' file from a NMM 3-hour forecast. The MOPS has been set up to work with data in the form that was used with the OMM (because it was adapted from the IMI): on a National Grid projection (NGP), and η-levels (height above orography). However, the NMM works with Unified Model (UM) grid and levels: on a (rotated) equatorial latitude-longitude projection (ELLP), and a hybrid combination of σ and pressure levels. The data structures are also very different: the NMM using the Fieldsfile structure (Bell [4]): the OMM using the Mesoscale Directory structure (Golding et al [9]). Therefore, it is necessary to interpolate from ELLP, hybrid level and UM variables to NGP, η-levels, OMM variables, the 'Forward Interpolation' (FI), before the MOPS analysis is carried out. Similarly, a reverse step, the 'Backward Interpolation' (BI) is carried out after the MOPS analysis. The final product of this step is a Fieldsfile containing analysed cloud fraction on the NMM grid for all wet levels (currently 27).

3.1 The forward interpolation

The forward interpolation involves the transfer of first guess data from an ELLP grid, hybrid levels, UM variables to a NGP grid, η-levels, and OMM variables. The program generates an output grid and levels which match the input grid and levels as closely as possible, rather than using fixed grid and levels. This process makes the program more versatile. The 'matching of the two grids on different projections reduces the detrimental impact of the interpolations. However, the 'level-matching' leads to a different set of height levels for each MOPS analysis.

3.1.1 Grid generation

The centre-point of the NGP grid is defined so as to match the NMM grid centre-point, and the NGP grid-spacing to match the NMM grid-spacing (see equation 5 and 6).

$$\Delta x = a\Delta\lambda \tag{5}$$

$$\Delta y = a\Delta\phi \tag{6}$$

where a is the radius of the earth; Δx, Δy are the grid spacings of the NGP grid; $\Delta\lambda$, $\Delta\phi$ are the grid spacings of the ELLP grid.

The NGP grid is extended outwards until it encloses the NMM grid. The NGP grid parameters are calculated such that the bottom-left corner of the grid is specified to the nearest km and the grid spacing to the nearest metre, the greatest accuracy which the Mesoscale Dataset Headers will allow. For the current model domain, this produces a grid of 94 × 94 points, with a bottom left hand corner at (-443,-327) (National grid co-ordinate in kilometres), and a grid-spacing of 16.68 km.

3.1.2 Horizontal interpolation

In the horizontal interpolation, the output grid-points are mapped onto the input-grid, and a bi-linear interpolation to these points is carried out; any output grid-points which lie outside the input grid assume the value of the nearest point within the bounds of the input grid.

3.1.3 Height level generation

Before the vertical interpolation is carried out, a set of η-levels which closely match the NMM levels, are defined. The height of each NMM level is calculated for each grid-point; these heights are averaged for each level, and this mean height above orography is taken as the height of the η-levels. Since the MOPS is concerned with moisture analysis, only the wet levels are used. The heights of the NMM levels are written to the output dataset to avoid the need to recalculate them for the BI.

3.1.4 Vertical Interpolation

The vertical interpolation is similar to the horizontal interpolation; η-levels are projected onto the NMM level structure and values are extracted. Any points above the top level assume the value at the top level, those below the bottom level take the value of the bottom level. For most variables, the values are obtained by linear interpolation, but cloud fraction is copied from the nearest level; this is to preserve the sharp top and base of cloud sheets. This 'interpolate/copy-option' for the cloud data is controlled through a namelist which is allocated at run-time. The dependency of the hybrid levels on the surface pressure and the temperature structure means that the exact levels heights will vary for each analysis. The maximum differences between the η-levels and the hybrid levels will occur in regions where the orography is high, with the hybrid levels being below the corresponding η-levels where the most extreme values occur. The differences are significantly less the layer thicknesses throughout the depth of the model, and increase with height as a fraction of layer thickness, from about 0.04 near the surface to nearer 0.3, towards the top of the model, where the NMM levels are virtually flat, but the OMM levels still follow the orography.

3.1.5 Variable transformation

The UM variables are also 'processed' to furnish the MOPS analysis with the variables in a form it can use: pressure (mb), potential temperature (deg C), cloud cover (oktas), relative humidity (%), specific cloud water/ice mixing ratio ($KgKg^{-1}$), height of hybrid levels (m) (used for backward interpolation), dynamic precipitation rate/phase ($mm\,hr^{-1}$), convective precipitation rate/phase ($mm\,hr^{-1}$), orographic height (m). These are calculated from surface pressure (Pa), level coefficients (A_k and B_k), potential temperature (K), cloud fraction, specific humidity mixing ratio ($KgKg^{-1}$), specific cloud water mixing ratio ($KgKg^{-1}$), specific cloud ice mixing ratio ($KgKg^{-1}$), dynamic rainfall rate ($Kg\,m^{-2}\,s^{-1}$), dynamic snowfall rate ($Kg\,m^{-2}\,s^{-1}$), convective rainfall rate ($Kg\,m^{-2}\,s^{-1}$), convective snowfall rate ($Kg\,m^{-2}\,s^{-1}$), orographic height (m), all of which are contained in the Mesout file. For a more detailed description of the derivation of these variables, see Barnes and Ballard [3].

3.2 Backward interpolation

The backward interpolation is practically the inverse of the forward interpolation, as would be expected, with the exception of the definition of the NGP grid and the η-levels, which are already defined. The vertical interpolation is carried out before the horizontal interpolation, with the NMM grid-points and levels being projected onto the OMM grid and levels. The only field which is transformed back to the NMM grid is cloud cover. This is interpolated bi-linearly in the horizontal, but in the vertical the value is copied from the nearest level. The cloud cover (oktas) is converted to a cloud fraction value.

4 Assimilation of MOPS data

Before the MOPS cloud data are assimilated there is one further processing step: the conversion of the cloud fraction fields to relative humidity profiles in the Acobs format. These are then assimilated as though they were radiosonde data, but with with a single grid-point of influence.

4.1 Conversion to relative humidity

The MOPS cloud data are in the form of fields of cloud fraction values following the BI, but they are assimilated as relative humidity (RH) profiles in the Analysis Correction (AC) scheme. Thus, they must be converted and written out in the 'Acobs file' format. This is carried out within the 'Acobs creation program', a new MOPS type of observation has been added and new routines included.

Table 7: Error ratios assigned to the MOPS relative humidity values at different model levels

Level	Error ratio
1–10	0.833
11	0.83
12	0.82
13	0.81
14	0.80
15	0.78
16	0.75
17	0.72
18	0.69
19	0.67
20	0.68
21	0.70
22	0.75
23	0.80
24	0.85
25	0.90
26	0.95
27	1.00

The conversion from cloud fraction to RH for the current operational cloud scheme is carried using the equations P292.18 to P292.21 from Smith et al [18]. In their rearranged form these become equations 7 to 9.

For $CF = 0$

$$RH \leq RH_{crit} \tag{7}$$

For $0 < CF < \frac{1}{2}$

$$RH = RH_{crit} - \frac{2\sqrt{2}}{2}(1 - RH_{crit}) \cos\left(3\cos^{-1}\left(\frac{\sqrt{CF}}{2}\right)\right) \tag{8}$$

For $0.5 \leq CF \leq 1$

$$RH = 1 - \frac{\sqrt{2}}{2}(1 - RH_{crit})(1 - CF)^{\frac{3}{2}} \tag{9}$$

where RH is the relative humidity (fractional), RH_{crit} is the 'critical' relative humidity (at which condensation starts to occur in the model) and CF is the cloud fraction. For equation 7, when there is no cloud, the point is flagged by setting the RH value to -0.85. The value of RH_{crit} is level-dependent and consistent with the values being used in the model; Currently RH_{crit} is 0.925 for the bottom 7 levels and 0.85 at all other levels.

When the Acobs file is created, a ratio of observation error to model background error is assigned to each RH value. The level-dependent error ratios which are currently used are shown in table 7. They are typical of current operational values for UK radiosondes up to to level 20 (marked on table 7 with a double line). Above this height of around 7 km, radiosonde humidity data are not used, as the sensor is unreliable below $-40\,\mathrm{deg}\,C$. In the absence of reference values from sonde data at upper levels, error ratios for MOPS data tend empirically towards 1.0 at the top wet level.

4.2 Assimilation technique

The MOPS RH values are assimilated by the Analysis Correction (AC) data assimilation scheme in the same way as radiosonde humidities, except that they are only allowed to influence a single grid-point. A RH increment is calculated using equation 10.

$$\Delta RH = RH_{MOPS} - RH_{model} \tag{10}$$

where RH_{MOPS} is the derived value from MOPS, and RH_{model} is the current model value.

In regions where RH_{MOPS} is equal to -0.85 (no cloud analysed), the RH increments are calculated according to equations 11 and 12.

For $RH_{model} > RH_{crit}$

$$\Delta RH = RH_{crit} - RH_{model} \tag{11}$$

For $RH_{model} \leq RH_{crit}$

$$\Delta RH = 0 \tag{12}$$

This has the effect of drying out cloudy regions in the model which have been analysed cloud-free.

5 Future developments

5.1 Rationalisation and automation

The MOPS analysis has been implemented as an option in the Mesoscale Graphics Facility (MGF), a large piece of software, much of which is not connected directly (or required for) the MOPS analysis. It is planned to produce a version which is devoted solely to the MOPS analysis. It is also intended to automate the whole procedure; this will allow the majority of the current code, which is responsible for the graphical display to be stripped away, leaving a much smaller piece of software. The formation of an MGF-independent MOPS analysis and the automation of the procedure may well be carried out simultaneously. The main reasons for automation, are the freeing of human resources and the reduction in the time required to perform the analysis, making it easier to schedule the procedure and, possible, bringing forward the availability time of the forecast.

The moisture analysis depends quite markedly on human quality-control (QC) and decision making in its use of imagery products (sections 2.4.2 and 2.4.4). In order to automate the MOPS analysis, it is necessary to develop safe methods of using the imagery products, and extend the range of imagery products used within the MOPS (this will probably be a direct consequence of the first aim). There are a number of problems with the automatic use of imagery at present, which are outlined below:

The automatic use of corrupt imagery products can lead to gross errors in the total cloud cover, cloud top height or precipitation analyses which can in turn corrupt the 3D cloud analysis and the diagnosed values of relative humidity. At present detection of corrupt images is carried out by the forecaster, as no other quality control is operated. It may be possible to make use of corrupt data flags, either in the header or the data itself to avoid using corrupt data or introduce imagery quality control checks into the MOPS. However, the whole process of imagery quality control and rejection would be better done within Autosat-2, the system which provides the majority of the satellite imagery..

The total cloud cover is diagnosed from the Meteosat infrared image by checking where there is a temperature difference of $10\,\mathrm{deg}\,C$ or more between the image brightness temperatures and the model surface temperatures; this is quite a large difference, which can cause problems when the two temperatures are similar (warm low cloud and cold surface), but it should be possible to reduce it without degrading the detection of cloud. Another, and probably better solution, will be to use some Autosat-2 derived-products [1], as they become available.

The assignment of cloud top height is made by matching the brightness temperature of the infrared image with a model temperature, and 'reading off' the height, by scanning upwards though the levels. Cloud top is usually associated with a temperature inversion, which can be very marked for persistent stratocumulus sheets; if this is not well-resolved by the model, the matched temperature will not correspond to the cloud deck, but to some point much higher where the cloud-free environment temperature has dropped to the satellite-observed value, which can lead to height assignment errors of several thousand feet. It may be possible to detect some of these type of errors using radiosonde profiles, but the coverage is very limited. Work is in progress on other methods of cloud top height assignment which may be useful for stratocumulus cloud (Hand [12]); the MOPS analysis should benefit from this work.

A further aspect in the automation is the quality control (QC) of the surface observations; at present there is no QC. If observation increments are analysed using the Recursive Filter (Purser [15]), their weighting is dependent on the observation-minus-background value, which should remove gross errors. However, because of the discontinuous nature of the variables being considered within the MOPS, it is the values, rather than the increments which are analysed. As a consequence, this aspect of the QC

is inappropriate as it is currently applied (see section 2.1), although it could be adapted to apply a correct observation-minus-background check (Veitch et al [19]). However, this whole approach may not be appropriate for such a discontinuous variable, so it may necessary to instigate a different QC procedure.

5.2 Quality estimate

There is a danger of simply nudging towards the model first-guess in areas devoid of observations, which is likely to be detrimental to the assimilation process as it may reduce the good impact of other forms of data ingested by the assimilation scheme. To this end it may be useful to develop a flagging system to indicate the extent to which the analyses reflect the observations or the first-guess fields.

One approach which could be adopted, is to have a 3D 'quality flag' (QF) array, with each cloud cover value having a corresponding QF value. This QF array would assume values in the range 0 to 1 in the course of the analysis procedure; 1 representing a value purely determined by the observations, 0 representing a value containing only first guess information. Each time observation data were used within the cloud analysis, adjustments would be made to the QFs to try and represent the impact of these data on the cloud fields. On completion of the MOPS analysis, all the cloud cover values which have a quality flag value below a certain threshold would be set to a missing data value to prevent the value being nudged towards within the assimilation scheme. For more detailed discussion of this idea, see Macpherson and Wright [13] (section 2.4.2).

5.3 Use of new imagery

The use of new imagery products available through the Autosat-2 system [1] may go some way to solving the current problems with the automatic use of satellite imagery. An albedo (sun-angle normalised visible) image will provide a much more reliable estimate of cloud cover; a cloud-mask product, which does a proper cloud detection using a number of data sources, including multiple image channels and model data, may provide an even better cloud cover analysis; it may be possible to use a fog product, which appears to detect both fog and low cloud, to diagnose the existence of stratocumulus sheets. A cloud top temperature product should simplify the derivation of cloud top height, but the problem with temperature inversions remains. Only visible, infrared and water vapour products are currently available from Meteosat, the derived products are only obtained from polar orbiting satellites, so, as an 'off-time' data source with a limited coverage, it will take careful consideration as how to make the best use of them. In addition, it is very unlikely that such imagery will be available for all analysis times.

As a short term alternative to the inclusion of polar orbiter data in the MOPS, it may be possible to make use of cloud observation files derived from the Advanced Very High Resolution Radiometer (AVHRR) imagery products for use in the Global and Limited-Area Models (Richards [16]). This approach would also have the advantage of allowing the assimilation of the data at the correct time.

5.4 Further development of the cloud analysis

Some of the assumptions used to interpret the cloud observations are loosely 'tied' to the OMM cloud and precipitation schemes (Golding and Ballard [10]). It may be that some of these assumptions are no longer appropriate for use with the NMM, with its different cloud and precipitation physics (Smith and Gregory [17]). This will require careful consideration.

There is potential for improvement in many areas of the MOPS analysis. It may be desirable to introduce a visibility analysis, to help initialise the low level humidity structure, in much the same way is presently done in the IMI (Ballard et al [2]), although it is planned to assimilate screen level dew point data directly into the model for the same purpose.

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